5.4 Solid Waste

Figure 22 shows the annual production of solid waste from the system. Non-hazardous solid waste was found to be the only solid waste produced in any significant quantity. TEAM defines several types of waste, and reports that unspecified, and municipal and industrial, can be combined to represent non-hazardous (See Table 23). The yearly variation in solid waste generation is the result of intermittent decommissioning and production of trucks and farm equipment.

6.0 Results Specific to the Three Major Subsystems

6.1 Base Case Feedstock Production Results

As stated earlier, feedstock production accounts for 77% of the non power-plant system energy consumption. Figure 23 shows that fossil fuel use in farming operations consumes the majority of this energy (83% of feedstock energy, 64% of total system energy). The second largest consumer of energy is the transportation of fertilizers and herbicides to the field. This accounts for 9% of feedstock energy and 7% of total system energy consumption. Because of the natural gas required to manufacture ammonium nitrate and urea, fertilizer production accounts for 6% of the energy used in the feedstock production subsystem, and 5% of the total system energy.

Figure 24 shows the source of CO_2 emissions in feedstock production, excluding that absorbed by the biomass. As expected, diesel fuel combustion in farming operations accounts for most of the CO_2 emitted (79% feedstock, 49% system). Diesel fuel production, which includes extraction and processing, emits 7% (4% system), while farm chemical transportation emits 9% (5% system). CO_2 is emitted from natural gas reforming operations in nitrogen fertilizer production.

Particulate emissions in feedstock production are shown in Figure 25. Although the combustion of fossil fuels in tractors and chippers emits the majority of the particulates to the air (56% feedstock, 31% total), those from transportation of chemicals to the farm were also found to be significant (31% feedstock, 18% system). Additionally, because of prilling operations and coupled energy use, ammonium nitrate manufacturing produces 7% of the total particulates released in feedstock production, and 4% from the entire integrated system.

Non-methane hydrocarbon emissions (including VOCs) for the feedstock production subsystem are shown in Figure 26. The majority (45% of feedstock and 5% of system NMHC emissions) are released during diesel oil combustion, but it's interesting to note that one-third are emitted in extracting crude oil and producing diesel fuel. Farm chemicals transport also emits a significant fraction of feedstock NMHC.

Figure 22: Yearly Total Solid Waste

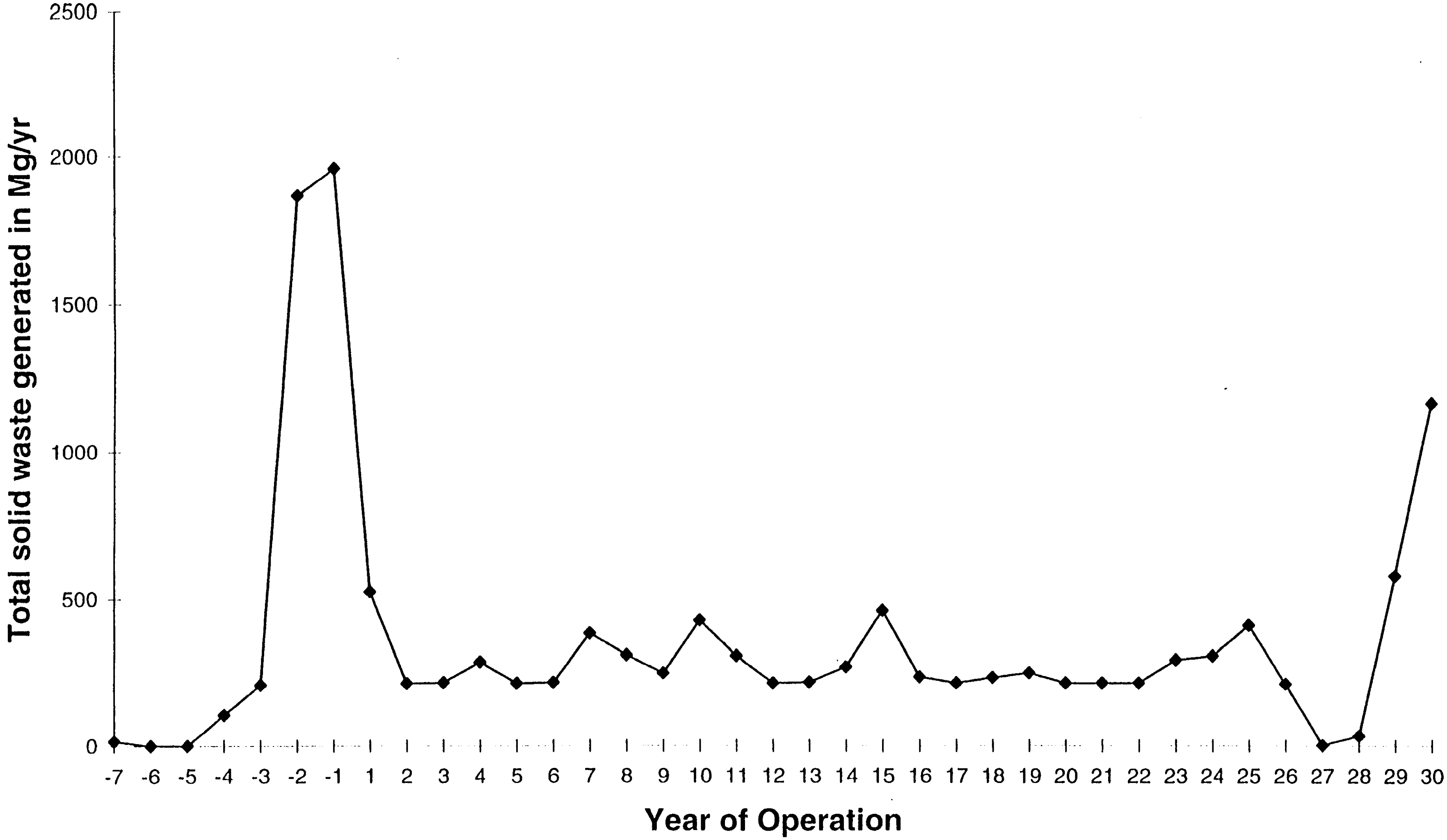


Figure 23: A Breakdown of Energy Consumption in Feedstock Production

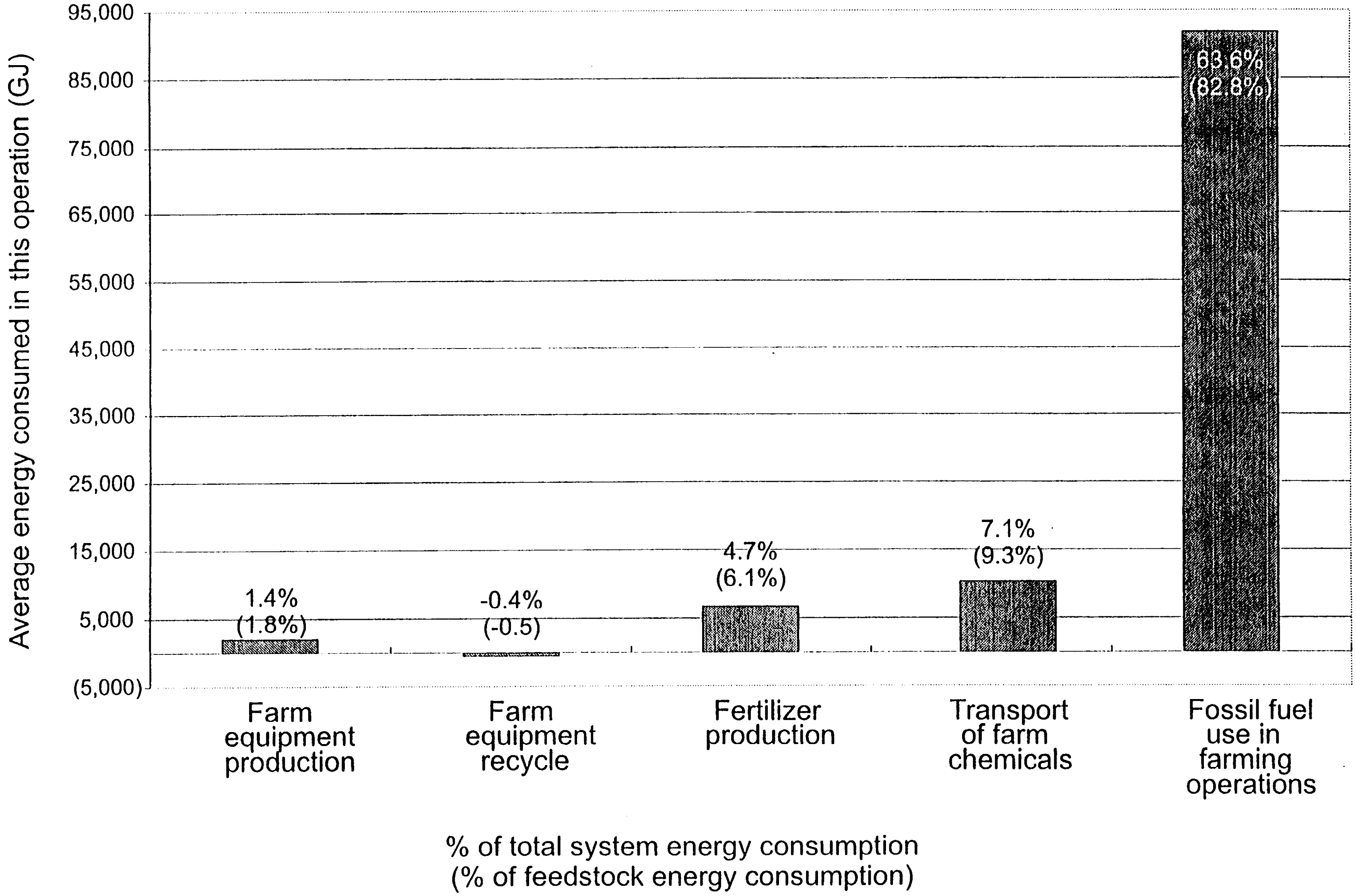


Figure 24: A Breakdown of CO_2 Emissions in Feedstock Production

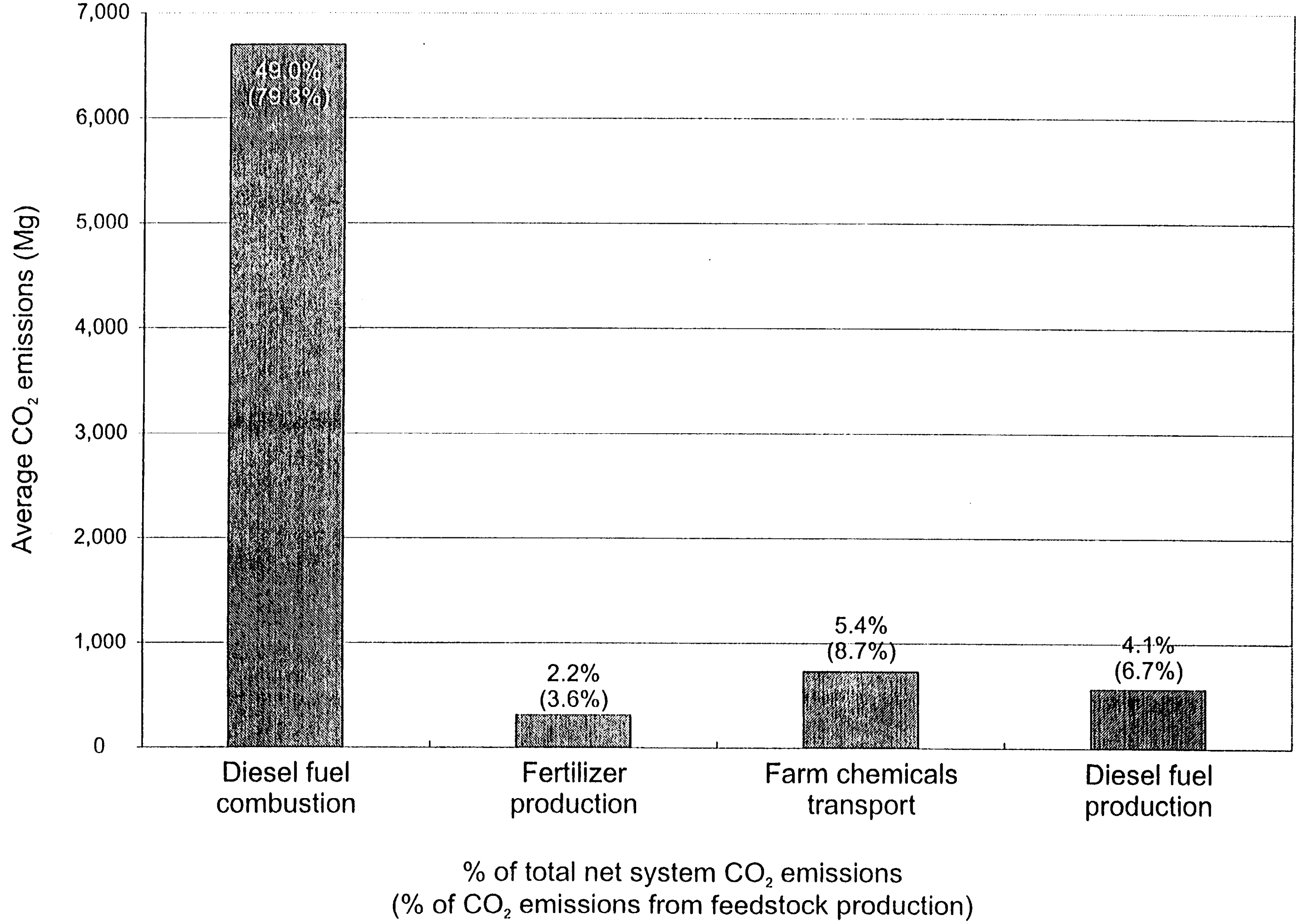
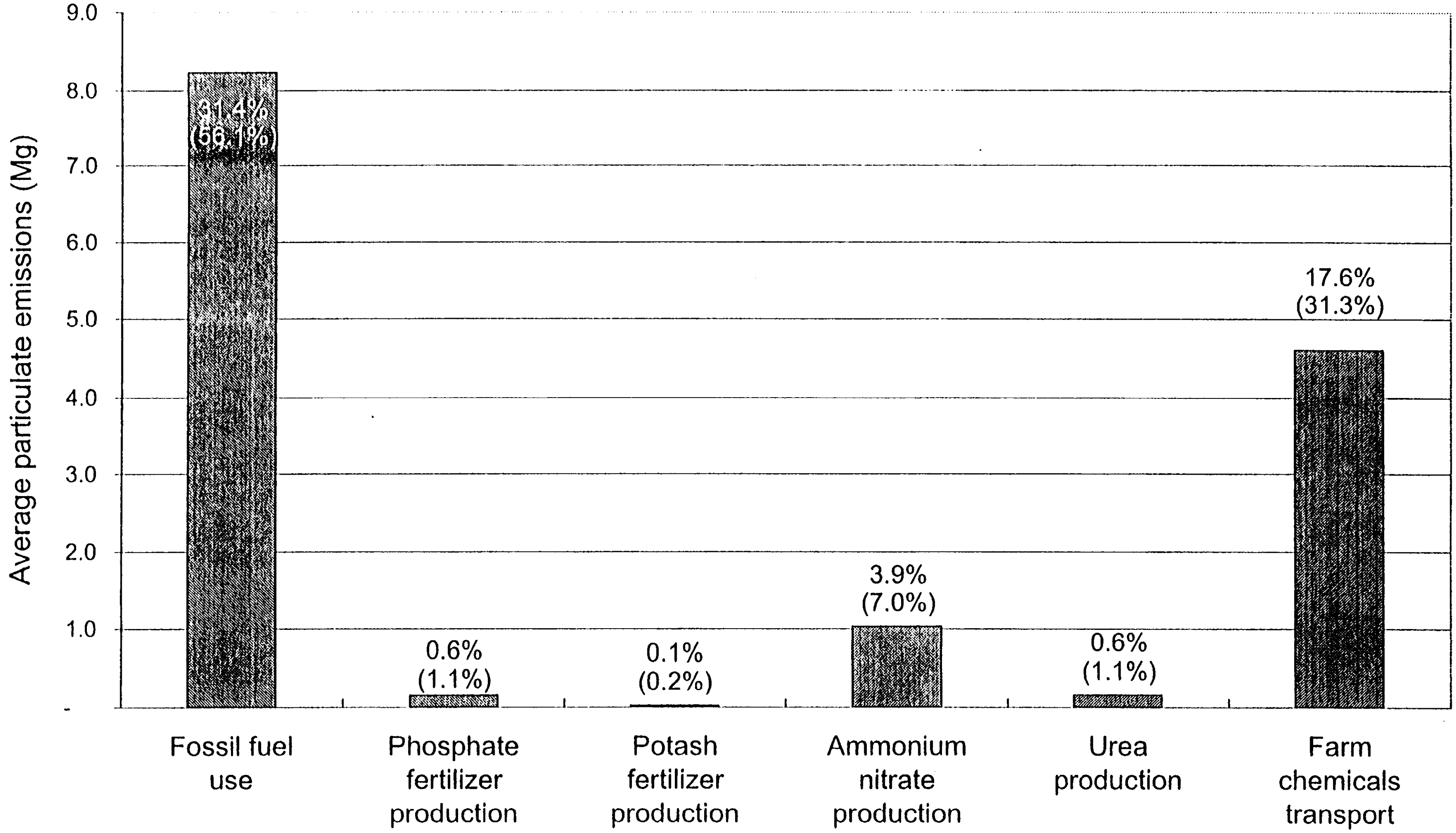
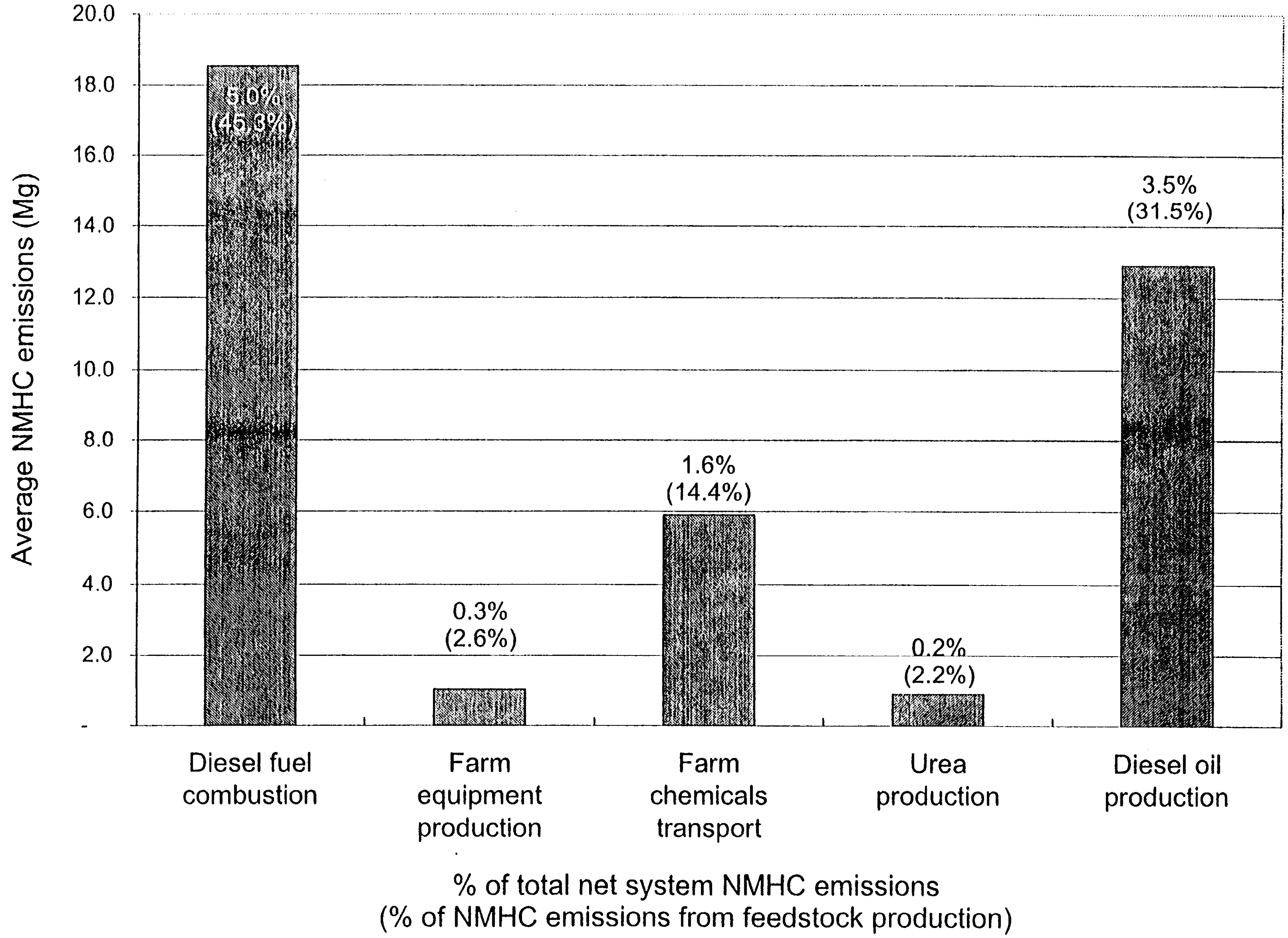


Figure 25: A Breakdown of Particulate Emissions in Feedstock Production



% of total net system particulate emissions
(% of particulate emissions from feedstock production)

Figure 26: A Breakdown of Non-Methane Hydrocarbon Emissions in Feedstock Production



Soil erosion rates will depend on specific site conditions and previous land uses. However, established and extensive root systems in short rotation woody crops minimize soil erosion and more efficiently take up nutrients than annual row crops which must establish new root systems each year (Thornton *et al*, 1997). Ranney and Mann (1994) estimate that soil erosion from short-rotation woody crops on a 5% slope will be 2,000 kg/ha/year, averaged over the life of the plantation. However, zero ground cover was assumed in deriving this number, and thus it may represent the worst case scenario. In order to obtain more reliable data, actual sediment losses are being measured in current field trials. Table 25 shows the sediment loss in ORNL's most recent field trials for the first two years of short rotation woody crops (Tolbert, 1997). Erosion rates at the plots without ground cover are expected to start to decrease to levels seen at plantations with cover as the trees mature. Note that the numbers presented in this table are for periods of three months. The highest erosion rates were typically associated with rainfall events and occurred during seasons when ground cover and crown cover were minimal. Therefore, it would not be correct to multiply the numbers shown in this table by four to obtain annual erosion values.

Table 25: Sediment Loss Measured in First Two Years of Growth in Recent Field Trials*

	Tree	Sediment Loss (kg/ha/three months)		
		Low value	High value	Average
Alabama A&M, with cover	Sweetgum	20	250	111
Alabama A&M, without cover	Sweetgum	280	1300	749
Ames Plantation, TN	Sycamore	10	105	30
Stoneville, MS	Cottonwood	0	250	91

Data from these same field trials have show that nitrogen and phosphorus movement into the surrounding environment is negligible compared with no-till corn (Tolbert *et al*, 1997). Further, the use of riparian filter strips can significantly mitigate the run-off of chemicals (Sears, 1996). Another possibility is to plant short rotation woody crops along the boundaries of current food crops. This would reduce the negative effects of chemicals leaching from row crops and satisfy some or all of the nutrient needs of energy crops at the same time.

N_2O represents only 0.01% by mass of the total air emissions shown in Table 19, and as discussed in section 5.1, has one-fifteenth of the global warming potential of CO_2 from this system. Approximately 96% of system N_2O emissions come from feedstock production, with the majority of those (58%) coming from diesel oil combustion during farming operations. Nitrification of fertilizers at the plantation is responsible for 40%. The high literature value for this source of N_2O was assumed to arrive at this number, and since emissions were not found to be substantial, further sensitivity runs with lower values were felt to be unnecessary.

6.2 Base Case Biomass Transportation Results

Of the three subsystems considered in this life cycle assessment (feedstock production, transportation, and electricity production), transportation requires the fewest resources and least amount of energy. The air and water emissions are also lowest from this subsystem. The resources, energy requirements, and emissions range from 2 - 19% of the total over the life of the plant (see Tables 19-23), with the majority around 4%. Therefore, any changes in the transportation subsystem will have some effect on the analysis but will not significantly change the overall impact of the system on the environment.

When comparing truck and train emissions, it is evident that transporting biomass by rail is less polluting. For the base case, the split was 70% by trucks and 30% by rail cars. However, as shown in Table 26, the split of stressors from these two modes of transportation is greater than 70/30. This table shows that most of the transportation emissions (by weight) are split with 26% from rail car use and 74% from truck use. However, transportation by rail car emits slightly more SOx to the atmosphere, but fewer CH_4, NOx, CO, hydrocarbons and particulates. Less N_2O is released from this system because it incorporates some rail transport than would be if the sole mode of transportation was by truck.

6.3 Base Case Power Plant Construction & Decommissioning Results

The main emissions from cement manufacturing are particulate matter, NOx, SOx, CO_2, and CO. Small amounts of volatile organic compounds, ammonia, chlorine, and hydrogen chloride may also be emitted. Sources of particulates include quarrying and crushing, raw material storage, grinding and blending, clinker production, and packaging and loading. Fuel combustion required for these processing steps produces nitrogen oxides, sulfur dioxide, carbon monoxide, and carbon dioxide. Sulfur dioxide is also generated from the sulfur compounds in the raw materials. Substantial quantities of CO_2 are produced through calcining of limestone through decomposition of $CaCO_3$ to CaO and CO_2. As can be seen in Figure 27, 83% of the CO_2 emissions emitted during construction are attributed to the production of cement. The second largest percentage of emissions is from steel production from ore. This result is expected since these two materials are used in the greatest quantity in power plant construction.

Table 27 is a breakdown of the emissions for each of the materials used in plant construction. They are shown as a percent of the total construction emissions. In general, the largest percentage of the overall emissions come from the processes involved in manufacturing cement followed by those required to produce steel. Aluminum production from ore is a very energy-intensive process, requiring more energy (2.7 times) than iron or steel production. This difference cannot be seen in Table 27 since the amount of aluminum used during plant construction is overshadowed by the steel requirement. Figures 28 and 29 show the breakdown of energy requirements in construction.

Table 26: Rail versus Truck Usage

		rail car use %	truck use %
Resources			
(r) Bauxite (Al2O3, ore)	kg	99.98%	0.02%
(r) Clay (in ground)	kg	18.13%	81.87%
(r) Coal (in ground)	kg	21.69%	78.31%
(r) Iron (Fe, ore)	kg	32.23%	67.77%
(r) Limestone (CaCO3, in ground)	kg	32.34%	67.66%
(r) Natural Gas (in ground)	kg	25.37%	74.63%
(r) Oil (in ground)	kg	26.36%	73.64%
(r) Sand (in ground)	kg	100.00%	0.00%
(r) Sodium Chloride (NaCl, in ground or in sea)	kg	87.70%	12.30%
(r) Uranium (U, ore)	kg	15.33%	84.67%
Aluminum Scrap	kg	100.00%	0.00%
Iron Scrap	kg	32.92%	67.08%
Lubricant	kg	16.37%	83.63%
Trinitrotoluene (C6H3(NO2)3)	kg	100.00%	0.00%
Water Used (total)	liter	30.68%	69.32%
Water: Unspecified Origin	liter	30.68%	69.32%
Air Emissions			
(a) Aldehydes	g	26.31%	73.69%
(a) Ammonia (NH3)	g	26.72%	73.28%
(a) Carbon Dioxide (CO2, fossil)	g	26.25%	73.75%
(a) Carbon Monoxide (CO)	g	37.10%	62.90%
(a) Chlorides (Cl-)	g	100.00%	0.00%
(a) Fluorides (F-)	g	41.74%	58.26%
(a) Non-methane hydrocarbons (including VOCs	g	20.70%	79.30%
(a) Hydrogen Chloride (HCl)	g	94.05%	5.95%
(a) Hydrogen Fluoride (HF)	g	71.70%	28.30%
(a) Hydrogen Sulfide (H2S)	g	18.13%	81.87%
(a) Metals (unspecified)	g	25.81%	74.19%
(a) Methane (CH4)	g	17.35%	82.65%
(a) Nitrogen Oxides (NOx as NO2)	g	27.34%	72.66%
(a) Nitrous Oxide (N2O)	g	4.85%	95.15%
(a) Organic Matter (unspecified)	g	26.30%	73.70%
(a) Particulates (unspecified)	g	24.00%	76.00%
(a) Sulfur Oxides (SOx as SO2)	g	55.68%	44.32%
(a) Tars (unspecified)	g	18.96%	81.04%
Water Emissions			
(w) Acids (H+)	g	33.60%	66.40%
(w) Ammonia (NH4+, NH3, as N)	g	29.85%	70.15%
(w) BOD5 (Biochemical Oxygen Demand)	g	26.43%	73.57%
(w) Chlorides (Cl-)	g	97.20%	2.80%
(w) COD (Chemical Oxygen Demand)	g	26.35%	73.65%
(w) Cyanides (CN-)	g	32.23%	67.77%
(w) Dissolved Matter (unspecified)	g	26.36%	73.64%
(w) Fluorides (F-)	g	29.87%	70.13%
(w) Inorganic Dissolved Matter (unspecified)	g	18.55%	81.45%
(w) Iron (Fe++, Fe3+)	g	15.33%	84.67%
(w) Metals (unspecified)	g	19.11%	80.89%
(w) Nitrates (NO3-)	g	15.33%	84.67%
(w) Nitrogenous Matter (unspecified, as N)	g	18.13%	81.87%
(w) Oils	g	25.25%	74.75%
(w) Organic Dissolved Matter (unspecified)	g	18.13%	81.87%
(w) Phenol (C6H6O)	g	31.79%	68.21%
(w) Sodium (Na+)	g	86.54%	13.46%
(w) Sulfates (SO4--)	g	82.75%	17.25%
(w) Sulfides (S--)	g	32.23%	67.77%
(w) Suspended Matter (unspecified)	g	19.84%	80.16%
(w) Tars (unspecified)	g	18.96%	81.04%
(w) Water: Chemically Polluted	liter	100.00%	0.00%
Energy			
Non-electric Enery Consumed	MJ	26.23%	73.77%
Electricity Consumed	MJ elec	19.93%	80.07%
Solid Wastes			
Recovered Matter (total)	kg	26.57%	73.43%
Waste (total)	kg	13.60%	86.40%

Figure 27: A Breakdown of Plant Construction CO2 Air Emissions

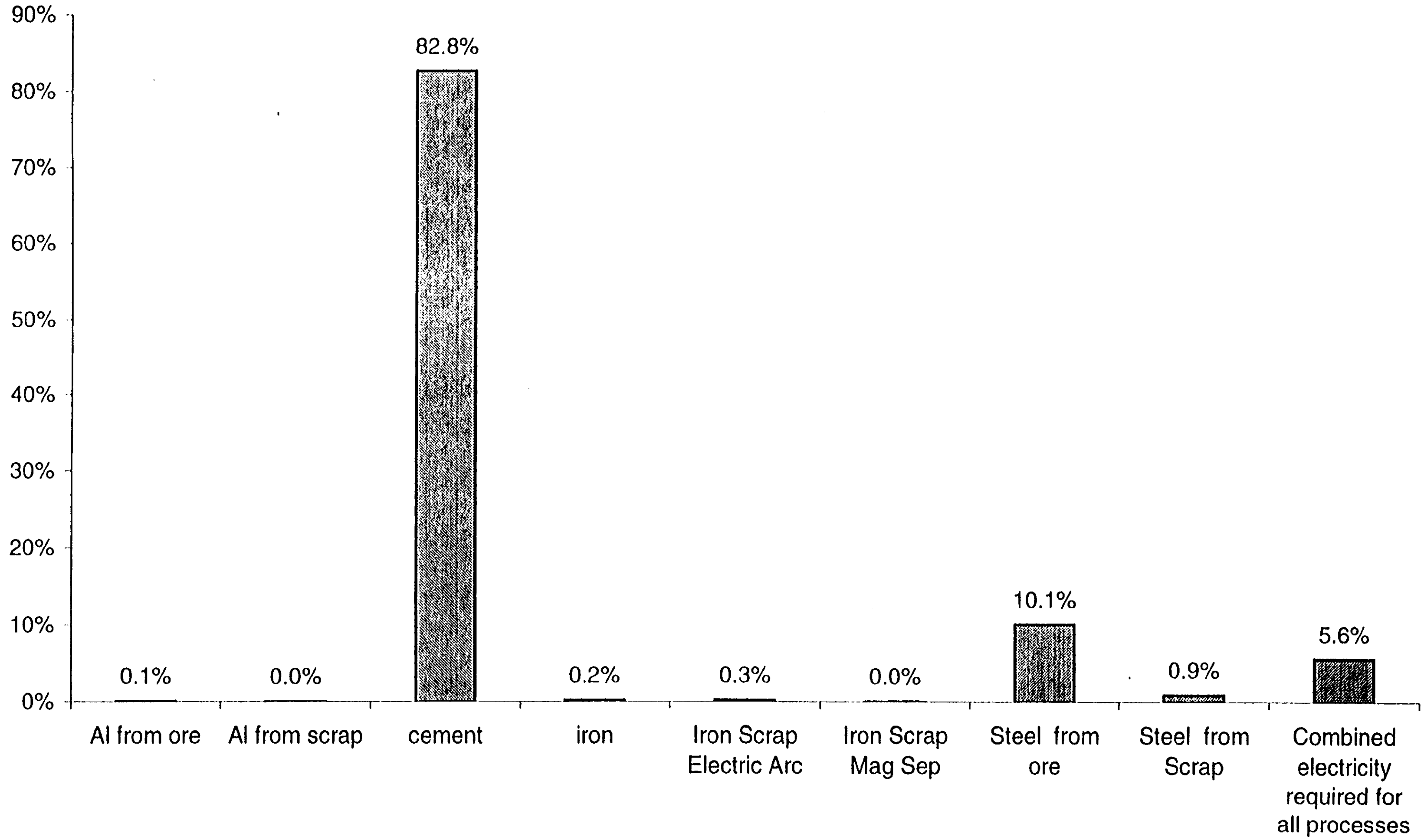


Table 27: Plant Construction Emissions

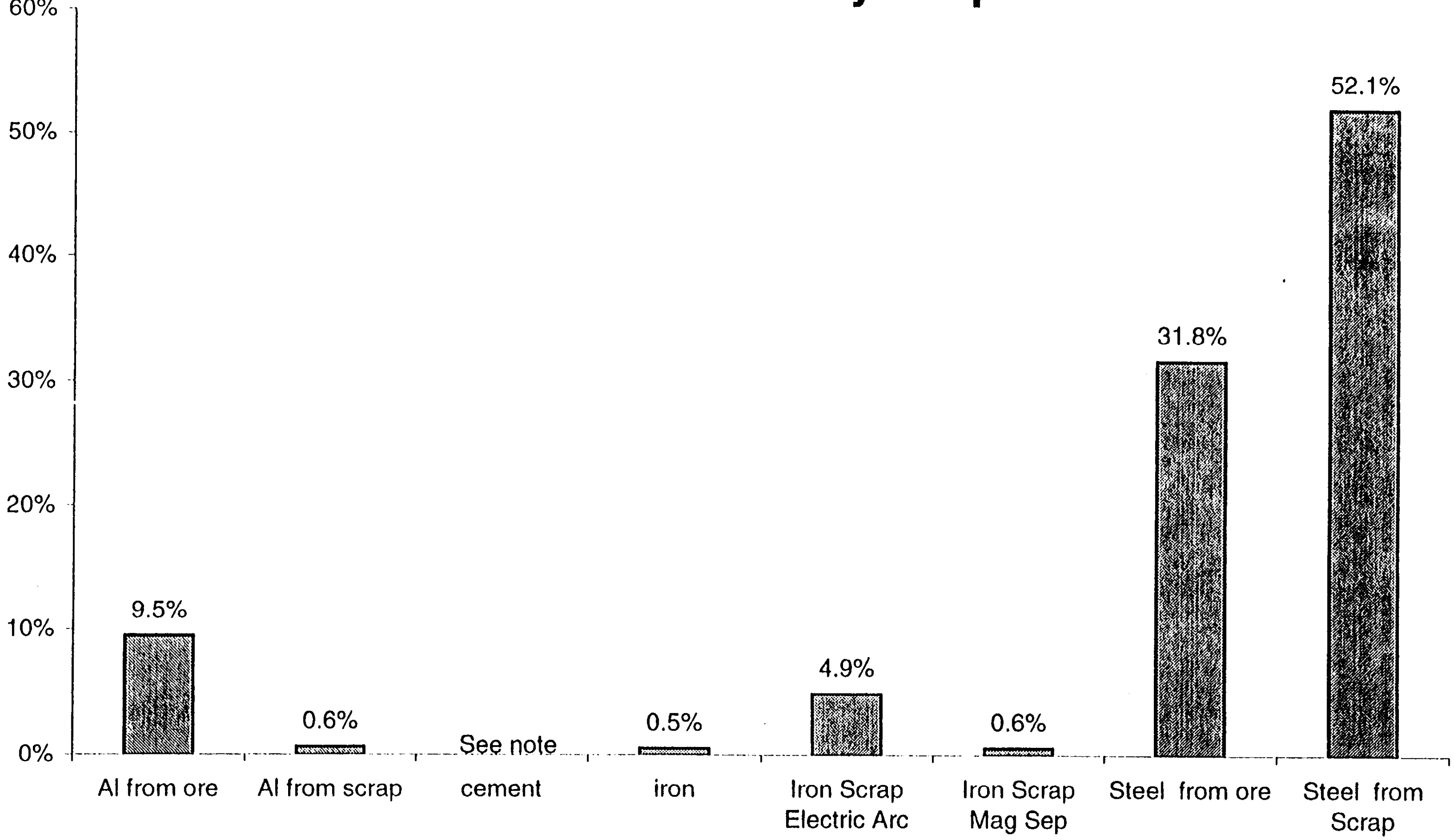
	Al from ore	Al from scrap	cement	iron	Iron Scrap Electric Arc	Iron Scrap Mag Sep	Steel from ore	Steel from Scrap	Combined electricity required for all processes
Aldehydes	1.43%	0.33%	0.00%	1.07%	4.05%	0.24%	48.85%	10.33%	33.69%
Ammonia (NH3)	0.13%	0.03%	0.00%	2.44%	0.37%	0.02%	96.21%	0.78%	0.01%
Carbon Dioxide (CO2)	0.11%	0.02%	82.76%	0.23%	0.26%	0.03%	10.06%	0.91%	5.62%
Carbon Monoxide (CO)	0.65%	0.01%	82.54%	0.16%	0.08%	0.01%	6.73%	8.71%	1.11%
Chlorides (Cl-)	50.00%	50.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fluorides (F-)	87.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	12.78%	0.22%
Non-methane hydrocarbons (including VOCs)	0.32%	0.06%	0.00%	1.36%	0.37%	0.08%	57.45%	4.52%	35.84%
Hydrogen Chloride (HCl)	10.36%	88.95%	0.00%	0.00%	0.00%	0.00%	0.00%	0.69%	0.00%
Hydrogen Fluoride (HF)	83.03%	0.00%	0.00%	0.42%	0.00%	0.00%	16.55%	0.00%	0.00%
Hydrogen Sulfide (H2S)	50.96%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	49.04%	0.00%
Metals (unspecified)	71.39%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	28.61%	0.00%
Methane (CH4)	2.22%	1.11%	0.00%	1.34%	1.11%	3.87%	57.89%	7.34%	25.12%
Nitrogen Oxides (NOx as NO2)	0.19%	0.02%	87.02%	0.05%	0.15%	0.02%	2.58%	0.83%	9.15%
Nitrous Oxide (N2O)	1.34%	0.32%	0.00%	0.94%	3.86%	0.28%	46.62%	13.22%	33.43%
Organic Matter (unspecified)	0.03%	0.01%	97.02%	0.03%	0.10%	0.01%	1.49%	0.26%	1.06%
Particulates (unspecified)	0.39%	0.01%	70.67%	0.67%	0.00%	0.00%	26.67%	0.31%	1.28%
Sulfur Oxides (SOx as SO2)	0.55%	0.09%	63.59%	0.20%	0.26%	0.02%	10.07%	2.52%	22.71%
Tars (unspecified)	54.19%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	45.81%	0.00%
BOD5 (Biochemical Oxygen Demand)	2.32%	0.12%	0.00%	2.22%	1.53%	0.09%	88.78%	4.89%	0.05%
COD (Chemical Oxygen Demand)	25.82%	0.92%	0.00%	0.06%	11.30%	0.67%	16.80%	44.09%	0.35%
Total Primary Energy	0.99%	0.14%	9.39%	1.09%	1.47%	0.18%	46.38%	5.27%	35.09%
Electricity	9.49%	0.64%		0.52%	4.91%	0.57%	31.82%	52.05%	

Iron Scrap Electric Arc = detinning of steel scrap & magnetic separation of steel scrap from mixed waste.

Iron Scrap Mag Sep = magnetic separation of steel scrap from mixed waste

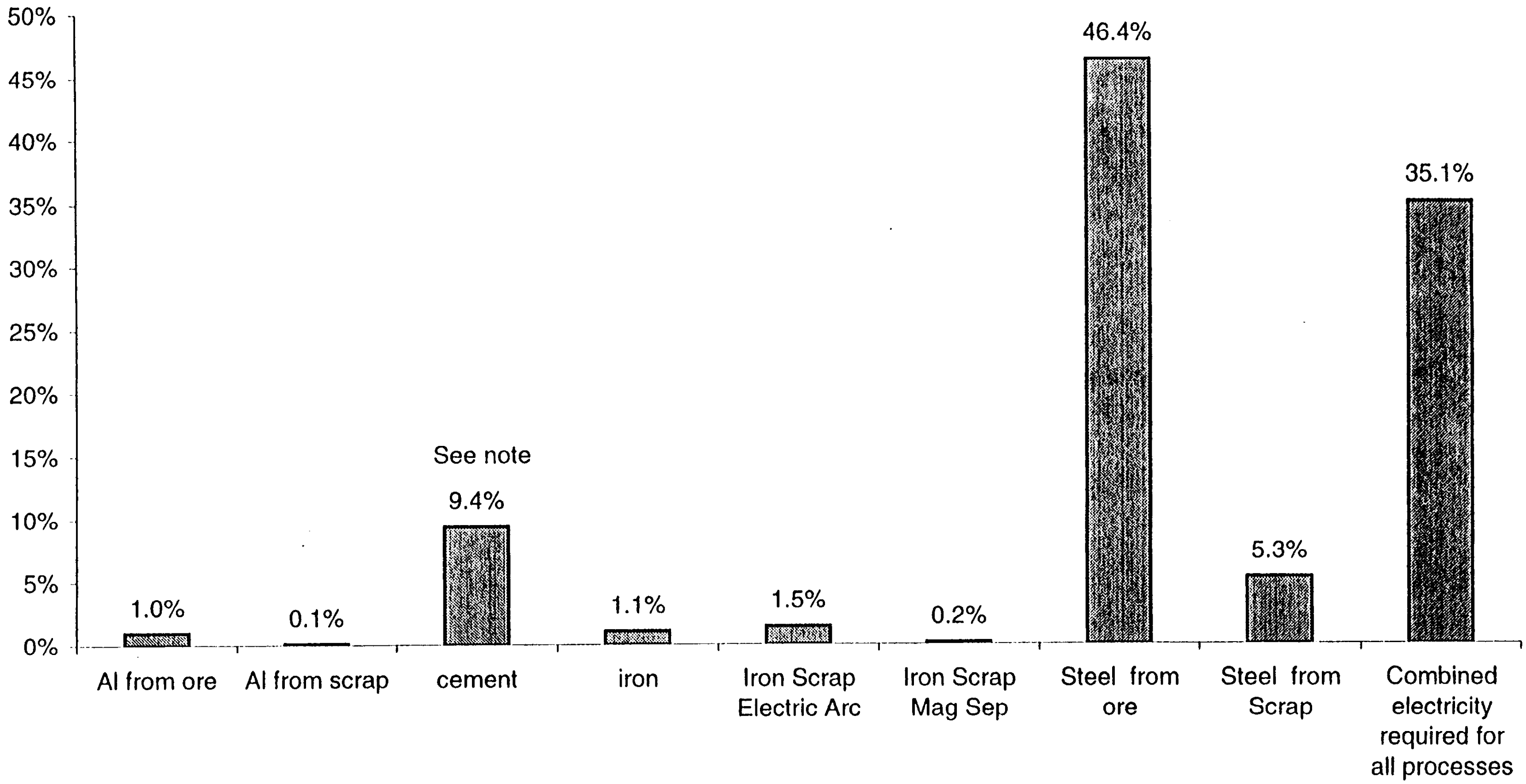
Percentages greater than 30% are shaded in gray.

Figure 28: A Breakdown of Plant Construction Electricity Requirements



Note: Total energy requirements for cement are shown on Figure 29;
data available do not distinguish between electric and non-electric energy requirements.

Figure 29: A Breakdown of Non-electric Energy Requirements for Plant Construction



Note: Energy requirements shown for cement include both electric and non-electric energy requirements; data available do not distinguish between these two types of energy.

Construction and demolition wastes will be produced in power plant construction and can be sent to a municipal solid waste landfill. Methane and CO_2 are the primary emissions from the landfill, produced by microorganisms under anaerobic conditions. At the end of the power plant's life, 75% of the materials of construction are recycled and 25% are landfilled. The recycling of materials is handled in the same manner as that described above under transportation (section 4.2).

In many of the previous figures, it is evident that some of the emissions in the two construction years are considerably higher than the average emissions over the life of the system. Table 28 contains a comparison of the construction emissions versus the total emissions in years negative one and negative two. The construction emissions are by far the majority of the emissions in these two years. However, it should be emphasized that the environment sees the emissions in the years that construction actually occurs and that these emissions are overshadowed by the feedstock, transportation, and operating emissions when summed up over the life of the system.

Table 28: Comparison of Construction and Total Emissions in Years -1 and -2

	Construction emissions averaged over 2 years [a]	Total emissions during the construction years averaged over 2 years [b]	Construction emissions as a percent of the total emissions in years -1 and -2
	(Mg/yr)	(Mg/yr)	(%)
NO_X	113	185	61%
SO_x	103	105	98%
CH_4	0.6	3.4	18%
CO	32	63	50%
particulates	147	170	86%
HC (except CH_4)	74	95	78%

Explanation of table
(a) (construction emissions in year negative two plus construction emissions in year negative one)/two
(b) (feedstock and construction emissions in year negative two plus feedstock and construction emissions in year negative one)/two
© = column (a) / column (b)

6.4 Base Case Power Generation Results

Although most of the resources consumed by the system are used in feedstock production, a significant amount is used in constructing the power plant. The bulk of the air and water emissions also come from the feedstock production subsystem. However, the power plant emits the vast majority of NOx, SOx, and VOCs. Details on stressors specific to the power plant are given in previous sections.